LANSCE DIVISION RESEARCH REVIEW

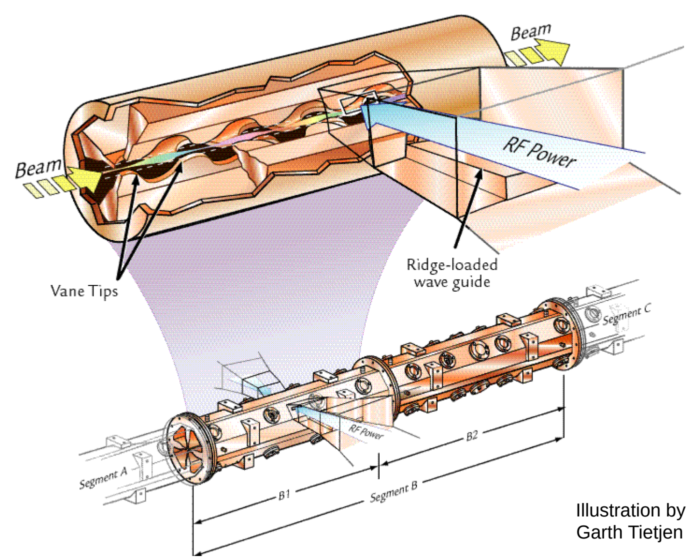
Continuous-Wave Radio-Frequency Quadrupole for the Low-Energy Demonstration Accelerator Successfully Reaches Design Limit

L. M. Young, D. E. Rees, A. H. Regan (SNS-PO), L. J. Rybarcyk (LANSCE-1), J. D. Schneider, H. V. Smith, Jr. (APT-TPO), D. L. Schrage (LANSCE-1), J. D. Sherman (LANSCE-2), M. E. Schulze (General Atomics Corporation)

For the Low-Energy Demonstration Accelerator (LEDA),[1] we designed and built a 350-MHz continuous wave (CW) radio-frequency quadrupole (RFQ).[2] This accelerator successfully accelerated, for the first time ever, a 100-mA CW proton beam from 75 keV to 6.7 MeV for more than eight hours. To prepare the RFQ to accelerate the proton beam, we used a process known as high-power RF conditioning to clean and condition the surfaces in the RFQ. This technique is important in reaching high peak fields in most types of RF accelerators. When operating the RFQ at the RF power level for which it was designed, the peak electrical field on the vane tips is 33 MV/m. The RFQ dissipates 1.2 MW of RF power. At this power level, the average RF power dissipation is 13 W/cm² on the outer walls near the high-energy end of the RFQ. We conditioned the RFQ with the high-power RF at power levels in excess of 1.4-MW CW and with pulsed beam before we obtained reliable operation with the 100-mA CW proton beam. RF power from a low-level RF (LLRF) system is amplified by three klystrons. The amplified RF power then travels to the RFQ through waveguides. Each klystron has a very large power rating of 1.3 MW. To prevent damage to the wave-guide vacuum windows, we split the power from each klystron two ways. These vacuum windows isolate the air in the waveguide from the vacuum in the RFQ, but they allow the RF power to pass through.

LEDA Configuration

LEDA was constructed to confirm the design and demonstrate the viability (at full power) of the most technically challenging components of the Accelerator Production of Tritium (APT) plant accelerator. On December 22, 1998, Secretary of Energy Bill Richardson announced that commercial light-water reactors will be the primary tritium-supply technology, and he designated APT as the backup technology for tritium supply. The LEDA RFQ consists of four 2-m-long RFQs resonantly coupled together to form an 8-m-long structure (Fig. 1).



▲ *Fig. 1. A solenoid magnet (not shown) focuses beam from the ion source into the low-energy end (Segment A) of the RFQ. As the beam travels through the RFQ gaining energy, the vane-tip modulation wavelength becomes longer. Radio-frequency power enters the RFQ at Section B1 (and D1) through small slots, known as irises, which are located between the ridge-loaded waveguides and the RFQ. The RF electric field accelerates and focuses the beam as it travels through the RFQ.*

These segments are labeled A, B, C, and D starting from the low-energy end. Radio-frequency drive ports are located on the B1 and D1 segments where the RF power is coupled into the RFQ through a half-height WR2300 waveguide and a section of tapered, ridge-loaded waveguide connected to a coupling iris. The tapered waveguide has the dimensions of the half-height WR2300 waveguide at one end and tapers to only 7 in. wide at the iris. The gap between the top and bottom ridges of the ridge-loaded waveguide slowly decreases as the cross section decreases in size toward the 7-in.-wide waveguide at the iris.

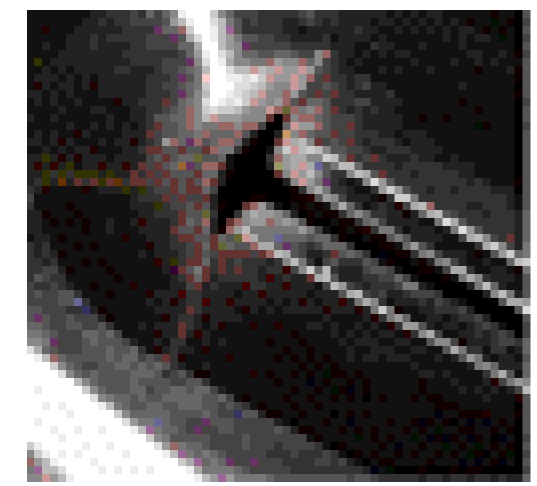
Initial Conditioning

New RF accelerators have impurities absorbed in the material from which they are constructed, copper in this case. Because the vacuum in an accelerator is never perfect, the RF fields accelerate residual ionized gas molecules that exist in the vacuum. When an accelerated gas molecule impacts the surface it drives out some of the absorbed impurities that are then captured by the vacuum pumps. Impurities and sharp edges lower peak electric fields, which can be sustained at the surface of the RFQ vane tips. High-power RF (HPRF) conditioning, which cleans the surfaces in the RFQ, is a critical step in reaching high peak electric fields in most types of RF accelerators. At sufficiently high RF levels, electric breakdown or sparking will occur between the vane tips. Through HPRF conditioning, the sparking will boil out impurities and smooth the surface of sharp edges, which cause the sparking. After an initial demonstration, HPRF conditioning began in earnest on November 20, 1998.

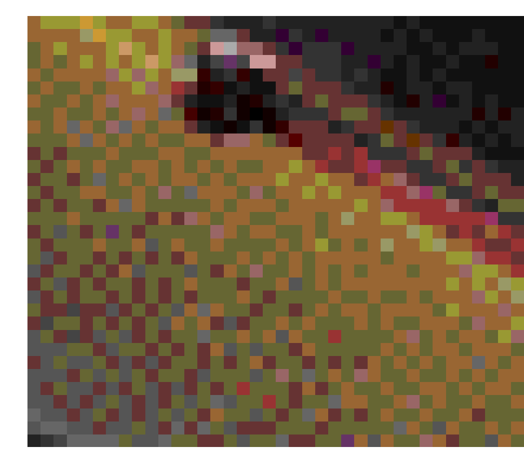
A phenomenon known as multipacting, which occurred in the tapered section of the waveguide, slowed our progress in conditioning the RFQ. Multipacting occurs when electrons are accelerated from one surface of the waveguide to the other in exactly half an RF period. When the electrons strike the surface more electrons are released. A build up of these resonant electrons causes the vacuum to degrade. At low RF power levels the multipacting occurs close to the iris where the gap is slightly greater than 1/16 in. As the RF power increases, the position where the multipacting occurs moves up the tapered section toward the WR2300 waveguide. At the halfway point in the tapered section, the gap is 2.9 cm. According to theory, multipacting can occur with the RF power at 68 kW, which is approximately the limit for simple half-cycle multipacting (described above). To mitigate the multipacting problem, we reconfigured the system and reduced the number of RF waveguide feeds by a factor of two. We are now using one klystron on segment B and only feeding quadrants 3 and 4 of that segment. On segment D, we use two klystrons, each feeding two quadrants. Our original plan used one klystron per segment to drive segments B, C, and D with each klystron driving all 4 quadrants of each segment. Previously, with two klystrons attached to the RFQ, we had to drive the RFQ with at least 800 kW to be above the power level where multipacting was a problem. If we stayed with our original plan, the multipacting would occur at 1.2 MW with three klystrons, which is our design power level without beam. By halving the number of waveguide feeds, we have reduced the multipacting to be only an occasional nuisance.

Iris Melting

When the conditioning process resumed on January 5, 1999, we soon achieved 1.2 MW of net RF power in the RFQ. However, the reflected power on the D-segment waveguide network increased to 10% instead of the 2% observed on December 24, 1999, the date of the previous test. Also, the frequency of the RFQ was 80 kHz lower than previously measured. While looking for the cause of the high-reflected power, we removed the window on quadrant 3 of segment D and discovered that some melting had occurred at both ends of the iris. Figure 2 is a picture of an iris removed from the RFQ in April 1999. A MAFIA code calculation on a simplified model of the iris showed the RF currents at the ends of the iris slot were enhanced by a factor of 10 over the RFQ wall current. The copper iris plate was only 1/16 in. thick at this point. This localized heating coupled with the increase in surface resistance at elevated temperatures was enough to melt the ends of the iris slots when the RFQ was operated with CW RF power at close to the design fields. The model results also showed that by increasing the thickness of the iris plate to 3/8 in., the size of the hole at the end of the slot more than doubles for the same coupling. This change reduces the enhancement of the wall currents from a factor of 10 to only 2.5. We replaced the original 1/16-in.-thick iris plates with 3/8-in.-thick iris plates (Fig. 3).



▲ *Fig. 2. Photo of melted iris.*



▲ *Fig. 3. Photo of new iris modified to reduce RF heating.*

Pulsed Beam

After January 27, 1999, but before the iris plates were replaced, the average RF power was restricted to less then 1 MW to prevent further damage to the irises. This meant that the RF power had to be pulsed whenever we raised the RF fields to the design value or above. During this period we integrated the LLRF, the HPRF, and the water-cooling system to reliably maintain the RF fields in the RFQ. The LLRF system sends a frequency error signal to the RFQ's water-cooling system. This cooling system adjusts the temperature of the water that cools the outer walls of the RFQ to maintain the 350-MHz resonant frequency. The cooling system also supplies 50°F water to cooling channels near the vane tips. The first pulsed beam was obtained on March 16, 1999. The beam current was increased slowly until April 8, 1999, when the RFQ accelerated a 72-mA pulsed beam at 10 Hz. The pulse length was 1.5 ms. This current was the highest obtained with two klystrons driving the RFQ.

Continuous Wave Beam Tests

On June 11, 1999, after reconfiguring the system and after two weeks of RF conditioning, we operated the RFQ CW with the design fields for more than 30 minutes. The ion source was reconnected to the RFQ and testing with a pulsed beam resumed on June 18, 1999. We began CW beam tests August 9, 1999, and by September 17, 1999, we had accelerated 100 mA to 6.7 MeV CW. The maximum beam current that we were able to reach either pulsed or CW did not show any substantial improvement from August 10–24, 1999. Up to this time we were not able to make meaningful transmission measurements because the measured input current was less than the measured current out of the RFQ. Electrons flowing into the RFQ reduced the positive proton current measured by the toroid at the RFQ entrance. These electrons are responsible for neutralizing the space charge caused by the electrically charged protons. The presence of this space charge produces a significant electric field that tends to spread the beam. If electrons continue to flow into the RFQ, then the space charge is not being neutralized as well as it should be.

Using the computer code PARMELA, we performed a simulation of the beam traveling through the low-energy beam transport (LEBT) system with the proton beam's space charge neutralized at 98%, except for the last 10 cm in front of the RFQ. The results of this simulation showed that the beam could not be "matched" to the RFQ. To be matched, the beam must be the correct size and converge at the correct angle when it enters the RFQ. Space charge caused the beam to deflect so much that it no longer converged as it entered the RFQ. In this situation, the beam was "mismatched," which means that the beam was too small in some locations and too large in other locations where it was scraped off on the vane tips. The simulation further showed that the maximum beam current out of the RFQ with this LEBT configuration was only 89 mA, which is equal to the maximum pulse current that we obtained by August 23, 1999. We moved the solenoid that focused the beam into the RFQ closer to the RFQ in an effort to match the beam into the RFQ. The solenoid was 30 cm from the RFQ. Simulations showed that if we installed an electron trap to prevent the electrons from flowing into the RFQ and moved the solenoid 15 cm closer to the RFQ, then the beam could be matched into the RFQ. The electron trap is a ring with a negative 2-kV potential placed at the entrance of the RFQ through which the beam passes. The potential from this ring prevents electrons from going through it, but not protons. We made these changes to the LEBT on August 28–29, 1999. A water leak in the LEBT beam stop prevented us from running beam until September 7, 1999. But then we were able to reach our beam current goals in only 10 days after this change. We also were able to obtain realistic measurements of the transmission through the RFQ. The electron trap stopped electrons flowing into the RFQ and stopped the electrons from reducing the measured input current.

Near-Term Goals

From 11:00 a.m. on December 17, 1999, through 11:00 a.m. on December 22, 1999, we met our goal of running LEDA for eight hours with a CW beam current of 100 mA. However, we are still trying to eliminate the various causes of the beam turnoffs. Currently, most of the beam turnoffs have been caused when the injector sparks down, the RFQ frequency drifts too far from 350 MHz, or the control system malfunctions. When the injector provides a good low-divergent beam that is well matched into the RFQ, the frequency of the RFQ is very stable. Under these circumstances when the injector sparks down, the beam can usually be turned back on within a few seconds. We are working on the injector and other systems to improve the availability of beam from LEDA.

Beam-Halo Experiment

The next experiment to be performed with LEDA is called the beam-halo experiment. The present high-energy beam transport (HEBT) and beam dump will be moved to make room for a new beam line that will be placed between the RFQ and the HEBT. This new beam line will use the same quadrupole-focusing lattice that will also be used in the coupled-cavity drift-tube-linac (CCDTL) developed at LANSCE. The CCDTL will accelerate the beam from the LEDA RFQ to higher energy through the present HEBT and on to the beam dump. Special beam diagnostic devices will be placed on the beam line to measure "halo" from the beam—halo is a small portion of the beam that is outside the radius of the main part of the beam. Beam-transport theory and simulations with beam-transport codes indicate that a mismatched beam will generate a halo and that a matched beam will not. This experiment will be performed to verify the theory and the beam-transport codes.

References

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2. D. Schrage et al., "CW RFQ Fabrication and Engineering," in *Proceedings of the XIX International Linac Conference* (Argonne National Laboratory, ANL-98/28, 1998), 679-683.

For more information, contact Lloyd M. Young (SNS-PO), 505-667-1951, MS H824, lyoung@lanl.gov.

Produced by the LANSCE communications team: Barbara Maes, Sue Harper, Garth Tietjen, AnnMarie Dyson, and Grace Hollen.

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